A Distributed Prioritization Scheme Between Access Points for Densely Deployed Networks

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***Abstract*—Random backoff counter based contention schemes have some drawbacks. They are basically unfair in short periods and unable to provide differentiated services between participants. Since these drawbacks are more serious when the participants are access points rather than mobile nodes, we propose a prioritization scheme to enhance the short-term fairness and to give different priorities between them. Our proposed scheme consists of two parts: assigning higher priority to a long waiting access point and probabilistically giving one level higher priority to some access points for differentiation. Through analysis and simulation, we verify that our prioritization scheme enhances the short-term fairness and achieves the priority differentiation between participants.**

I. Introduction

In a densely deployed network, a more important metric for the network capacity is the signal to interference-plus-noise ratio (SINR) rather than the signal-to-noise ratio (SNR) [1] because of the interference from neighbor access points (APs). Since conventional power control based interference mitigation schemes are not enough to solve this severe interference problem, another interference mitigation schemes using frequency or time resources have been proposed [2], [3]

The resources should be scheduled in a distributed manner considering the nature of user-centric deployment. One of the most well known distributed scheduling schemes is the random backoff counter based carrier sense multiple access with collision avoidance (CSMA/CA) which is used in IEEE 802.11 [4]. However, it contains a lot of protocol overhead, so new distributed frequency domain based contention schemes have been recently proposed which are based on a multiple packet reception technique by multiple-input and multiple-output, (MIMO) or orthogonal frequency-division multiple access (OFDMA) [3], [5]–[7]. Because of the assumption of multiple packet reception, these schemes also assumed that the APs have multiple antennas. Among those, we consider two contention schemes in [3], [6] as our baseline contention schemes that are designed for femtocell and WLAN, respectively.

Previous investigations have only focused on designing a new frequency domain contention mechanism, and they have simply used the random backoff method as a way of choosing random numbers. Although the random backoff achieves perfect stochastic fairness, it shows poor short-term fairness [8]. Due to its short-term unfairness, the AP contention scheme causes a more serious problem than usual user contention schemes. This is because i) it gives a longer transmission time to the contention winner than legacy user contention schemes, and ii) from the user's view point, each user can get a chance to transmit or receive its packet after two consecutive winnings (AP and user contentions), resulting in increased wireless access delay. For instance, if an AP loses more than several consecutive times and a winner has 5 msec an exclusive channel use [3], the defeated AP cannot transmit any packet for tens of msec. If a user associated with the AP has been receiving a delay sensitive service such as voice over IP (VoIP) and video on demand (VoD), the service can be interrupted. Another problem in the random backoff scheme is that it cannot provide differentiated services between APs.

To solve the short-term unfairness and non-differentiated service problems, we propose a prioritization scheme for AP contention. Our scheme defines several priority classes where each class can choose a random number in a different range. This is similar to the prioritization scheme in 802.11e [4], which only assigns priorities according to service groups such as best effort, voice, and video while our scheme uses priority for fairness. In our scheme, an AP that has been defeated several consecutive times is allocated to a higher priority class, and the AP that won the last contention is allocated to a lower priority class. Also, we probabilistically gives higher or lower priority to an AP of interest if necessary.

The rest of the paper is organized as follows. We first describe the considered system model in Section II. Then, our prioritization scheme is presented in Section III. After evaluating the proposed scheme through analysis and simulation in Section V, we conclude our paper in Section VI.

II. System Model

We consider a densely deployed network that consists of many femto BSs or WLAN APs, and hereafter we only use the term AP. Each AP i is serving n_i users. We assume that all APs participate in contention to access the channel. For the AP contention mechanism, we basically consider either of the works in [3] and [6].

A new frame structure, which consists of a contention period and a data transmission period, is needed to implement the frequency based AP contention scheme. Fig. 1 shows an example topology and the frame structure for the AP contention scheme. Let C_j denote contention group j which is a set of APs. In this example, $C_1 = \{A1, A2, A3\}$ and $C_2 = \{A3, A4\}$. If all the APs transmit their packets

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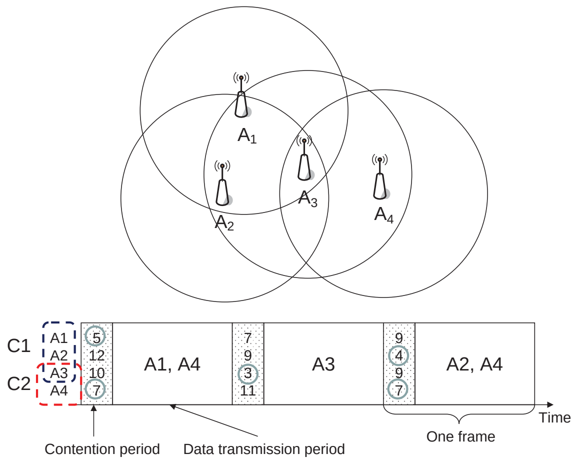

Fig. 1. Example topology and frame structure for the proposed AP contention scheme. There are two contention groups: C1={A1, A2, A3} and C2={A3, A4}. One frame consists of "Contention period" and "Data transmission period." The numbers in the contention period is random numbers chosen by APs, and the APs indicated in the data transmission period represent the contention winners.

simultaneously, the interference level will rise up. The AP contention scheme allows only one AP to be active in one contention group, resulting in higher network capacity. To this end, each AP chooses a random number and competes with the other APs in the same contention group at each contention period. The contention winner, i.e. the AP with a smallest random number, exclusively obtains the channel access right for the following data transmission period while the other APs cannot transmit anything in that period. To transmit and receive random numbers, each AP should have multiple antennas [6] or needs help from users [3] in addition to OFDMA technique. In this example, A1, A2, A3, and A4 choose their random numbers as 5, 12, 10, and 7, respectively, at the first frame. Then, A1 and A4 become the winner of each contention group. They use the following data transmission period without experiencing interference. For each frame, the same contention repeats and the winner exclusively uses the channel. Our prioritization scheme can work with any of the AP contention schemes in [3], [6]. This is because our scheme only deals with how to select random numbers.

III. Prioritization Algorithm

A. Prioritization Method and Goal

We consider several classes to classify the order of AP priorities. Each AP with the same priority class select a random number in a predetermined range. By assigning a different range to each priority class, the order of priorities among classes is guaranteed. For instance, let us assume that the maximum contention window (CW) size is 51 [6] and there are two priority classes. APs in the higher priority class and the other APs in the lower priority class can choose random numbers in [0, 26) and [26, 52), respectively. Therefore, an AP in the higher priority class always wins the contention. By assigning a non-overlapping CW range in each priority class, the priority inversion can be completely prevented. In this paper, we denote the lowest priority class as 0.

Let f_i denote the desirable fraction of frames of AP i, where $\sum_{i\in C_j} f_i \le 1$ for each contention group C_j. The goal needs to be flexible enough to cover diverse interests. One of the cases is perfect time fairness among APs in the same contention group. That is, $f_i = 1/|C_j|$ for $\forall i \in C_j$, where $|C_j|$ is the number of APs in the group. Another case is that the time resource allocation for each AP is proportional to the number of users in service, that is, $f_i = n_i / \sum_{k\in C_j} n_k$. There can be many other fairness criteria depending on the objectives. We do not cover this issue in this paper.

Let a_i denote the actual allocated fraction of frames to AP i. Our objective is to achieve $a_i = f_i$ as close as possible for all AP i under the constraint of the short-term fairness in a distributed manner.

B. Prioritization Scheme

To describe our scheme, we introduce two priority assignment schemes: default priority and priority compensation schemes. It is assumed that a feasible set of f_i is given according to the considered policy.

1) Default Priority Scheme: We give high priority to APs that have waited several frames for transmission. Let w_i denote the number of frames that AP i has been waiting for channel access. Then, the default priority of AP i is defined as

$$DP_i = \lfloor f_i(w_i + 1) \rfloor. \tag{1}$$

2) Priority Compensation Scheme: Since the default priority is not appropriate to meet the goal of $a_i = f_i$, an AP with higher f_i needs to be compensated by having one higher priority. After AP i settles down with the default priority, we probabilistically gives it one higher priority than DP_i according to f_i. Let CP_i denote the compensated priority of AP i. Then, we can express CP_i as

$$P(CP_i = DP_i) = 1 - f_i, \tag{2}$$

$$P(CP_i = DP_i + 1) = f_i. \tag{3}$$

This indicates that CP_i is either DP_i or $DP_i + 1$.

C. Operation Example

This section explains our proposed scheme through an example shown in Fig. 2. There are two APs with $f_1 = 0.75$ and $f_2 = 0.25$. The three numbers in parenthesis are DP_i, CP_i, and w_i, respectively. According to (1), A1 has $DP_1 = 1$ when it waits one frame ($\lfloor 0.75(1+1) \rfloor = 1$), while A2 has $DP_2 = 1$ when it waits three frames ($\lfloor 0.25(3+1) \rfloor = 1$). Owing to the priority compensation, A1 and A2 have chances to increase their priority with the probability of 0.75 and 0.25, respectively.

Initially, A1 and A2 have priority 0 as their default priorities since $w_1 = w_2 = 0$. By the priority compensation, A1 gets priority class 1 while A2 does not ($CP_1 = 1, CP_2 = 0$), so A1 wins the first round contention and uses the following data transmission period exclusively. At the next frame, their default priorities are still 0 and their compensated priorities are also 0. By the random number contention, A2 wins and transmits in the next data period. At frames 3 and 8, the default priority of A1 is 1 since $w_1 = 1$. Similarly, the default priority of A2 is 1 since $w_2 = 3$ and 4 at frames 6 and 7.

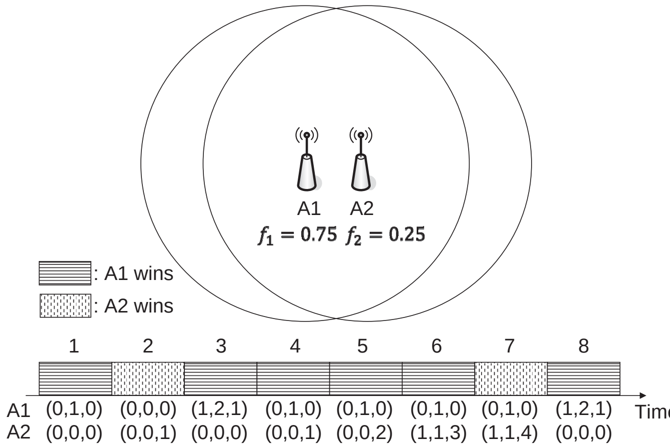

Fig. 2. An example of our proposed prioritization scheme. Among eight frames, six frames are consumed by A1 (frames 1, 3, 4, 5, 6, and 8) and two frames by A2 (frames 2 and 7). The 3-tuple in parenthesis stands for the default priority, the compensated priority, and the number of waiting frames, respectively.

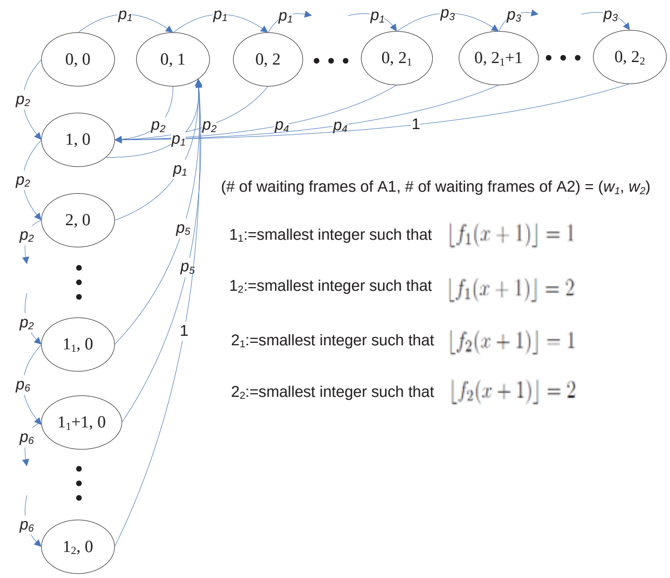

Fig. 3. Markov chain model for the case of 2 APs. Each state vector represents the numbers of waiting frames of A1 and A2, respectively.

D. Contention Overhead Reduction

In our prioritization scheme, the whole CW range is equally divided by the number of priority classes. To use our scheme, a large CW range is needed since a smaller CW range leads to higher collision probability. For instance, the work in [6] assumed that the maximum CW is 51. If we define four priority classes, each priority class has only 13 random numbers in pool. That is [0,13), [13,26), [26,39), and [39,51). If there are two APs in the same priority class, the collision probability is 1/13. For three APs, it is about 21.9%. Therefore, using a small number of priority classes is beneficial when CW is small. This means there exists a tradeoff relationship between the collision probability and the number of priority classes.

We now consider three priority limitation methods. First, we use only the default priority in assigning a priority class according to the number of frames that AP i has been waiting, w_i (1). The contention mechanism is the same as before. The drawback of this method is that the gap between a_i and f_i is big since it cannot take f_i into account for priority assignment.

Second, the method with only priority compensation considers assigning one level higher priority according to f_i as in eqs. (2) and (3). It is easy to prove that this method stochastically makes f_i equal to a_i if AP i belongs to only one contention group. However, it can't guarantee the short-term fairness. For instance, when $f_1 = f_2 = 0.5$, its assignment result is the same as that of the conventional non-priority scheme.

Last, we consider the scheme using both the default priority and priority compensation schemes with a priority limit. Before reaching the priority limit, this method allocates the same priority as our proposed scheme. However, when the priority to be assigned exceeds the priority limit, this method sets the compensated priority to the priority limit. Even though the achieved a_i in this method is not exactly equal to f_i, its error is much smaller than that in the first method. Also, it improves the short-term fairness, differently than the second method.

IV. Performance Analysis

In this section, we analyze the delay performance of our proposed prioritization scheme for a simple scenario of 2 APs. Fig. 3 shows the Markov chain model for our proposed scheme when there are two APs in one contention group. Each state is represented by the two elements of w_1 and w_2. i_x indicates the default priority changing point when $DP_i = x$. Since the default priority changes at this state, the state transition probability also changes. When A1 wins a contention at (y, 0) and (0, y) where y is an arbitrary number, next states are (0, 1) and (0, $y+1$), respectively, according to the state definition. Similarly, when A2 wins a contention at (y, 0) and (0, y), next states are ($y+1$, 0) and (1, 0), respectively. To get the state transition probabilities $(p_1, \cdots, p_6)$, we consider four cases: i) $CP_1 = DP_1$ and $CP_2 = DP_2$, ii) $CP_1 = DP_1$ and $CP_2 = DP_2 + 1$, iii) $CP_1 = DP_1 + 1$ and $CP_2 = DP_2$, and iv) $CP_1 = DP_1 + 1$ and $CP_2 = DP_2 + 1$. The transition probabilities of these four cases are $(1-f_1)(1-f_2)$, $f_1(1-f_2)$, $(1-f_1)f_2$, and $f_1 f_2$, respectively. When $DP_1 = DP_2 = 0$, the probability that A1 wins is

$$p_1 = (1-f_1)(1-f_2)/2 + f_1(1-f_2) + (1-f_1)f_2 \cdot 0 + f_1 f_2/2$$
$$= (1 + f_1 - f_2)/2 = f_1. \tag{4}$$

Similarly, we have $p_2 = f_2 = 1 - f_1$. Then, we obtain $p_3 = f_1^2/2$, $p_4 = 1 - f_1^2/2$, $p_5 = 1 - (1-f_1)^2/2$, and $p_6 = (1-f_1)^2/2$. With these transition probabilities, the steady state probabilities can be obtained. We can get the a_i, the expectation $\mathbb{E}[W_i]$, and its variance $\mathrm{Var}[W_i]$, where W_i is a random variable for the number of waiting frames of AP i.

Legacy scheme: The delay distribution of the legacy scheme, i.e. non-prioritized scheme, follows a geometric distribution. Regardless of the assignment results for the previous slots, each AP has the same probability of winning at each slot, i.e. $p = 0.5$. So, we have $P\{W_i = k\} = (1-p)^k p$. Then, we have $\mathbb{E}[W_i] = (1-p)/p = 1$ and $\text{Var}[W_i] = (1-p)/p^2 = 2$, respectively.

Proposed scheme with $f_1 = f_2 = 0.5$**:** In this case, there are seven states since $1_1 = 2_1 = 1$ and $1_2 = 2_2 = 3$. The state transition probabilities are $p_1 = p_2 = 1/2$, $p_3 = p_6 = 1/8$, and $p_4 = p_5 = 7/8$. We have $P\{W_i = 0\} = 9/73$, $P\{W_i = 1\} = 56/73$, $P\{W_i = 2\} = 7/73$, and $P\{W_i = 3\} = 1/73$ for $i \in \{1, 2\}$. Therefore, $\mathbb{E}[W_i] = 1$ and $\text{Var}[W_i] = 0.27397$.

While the expected waited times in the legacy and proposed schemes are the same, their variances are very different. In addition, in our proposed scheme, the probability that an AP keeps waiting for more than three frames is zero, i.e. $P\{W_i > 3\} = 0$, while that in the legacy scheme is 1/16=6.25%. It means that the short-term fairness in our proposed scheme is much better than that in the legacy scheme. Similarly, the numerical analysis can be extended to a case with more than two APs in the same contention group. In such a case, an n-dimensional Markov chain model is needed, where n is the number of APs in one contention group.

V. Performance Evaluation

In this section, we compare the performance of our proposed prioritization scheme with that of a legacy non-priority scheme in terms of the error and variance of W_i. The error is defined as the difference between the actual allocated and desired fractions of frames normalized by the actual allocated one, i.e. $|a_i - f_i|/a_i$. The variances of W_i indirectly indicate the short-term fairness. If the variance is small, the number of waiting frames varies around the mean value. In other words, an AP waits a similar number of frames. On the contrary, if the variance is large, each AP waits a very different number of frames, resulting in poor short-term fairness.

For performance comparison, we simulate a legacy 'No priority', 'DP only', 'PC only', and 'DP and PC' schemes with priority limits of one or three, where DP and PC stands for the default priority and priority compensation methods, respectively. In the case of the priority limit of one, there are two priority classes: zero and one. In simulations, we consider two or three APs for simple scenarios, and 50 APs for a randomly distributed scenario.

Note that we assume that there is no collision at the AP contention scheme among APs, that is, two or more APs choose the same contention number, since our targeted frequency based AP contention schemes proposed collision resolution algorithms in [3], [6].

A. Simple Scenarios

We consider three scenarios which are one 2-AP and two 3-AP network scenarios in the network. One of the 3-AP scenarios is that all the three APs are in one contention group, and the other 3-AP scenario is that the three APs are lined up so that A1 and A2 are in one contention group, and A2 and A3 are in the other contention group. We vary f_1 from 0.1 to 0.9 with the interval of 0.1, and set the number of frame transmissions for each set-up as 100 million times.

Fig. 4 shows the error performance in these simple scenarios. The simulation results are almost the same as the numerical results of the 2-AP scenario. 'No priority' scheme shows the worst performance since it allocates the two APs an equal number of frames regardless of f_i. 'DP only w/ lim 1' scheme shows the performance with large error since DP is activated by a sufficient number of waiting frames. The other three schemes achieve less than 10% error performance. Especially, the average error performances of our proposed 'DP+PC w/ lim 1' and 'DP+PC w/ lim 3' schemes are 2.49% and 1.93%, respectively, when we vary f_1 from 0.3 to 0.7. 'PC only w/ lim 1' scheme shows the best error performance since it does not consider w_i.

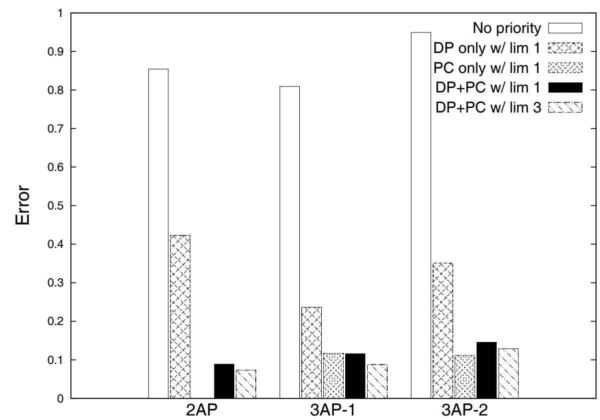

Fig. 4. The error performances of the simple scenarios.

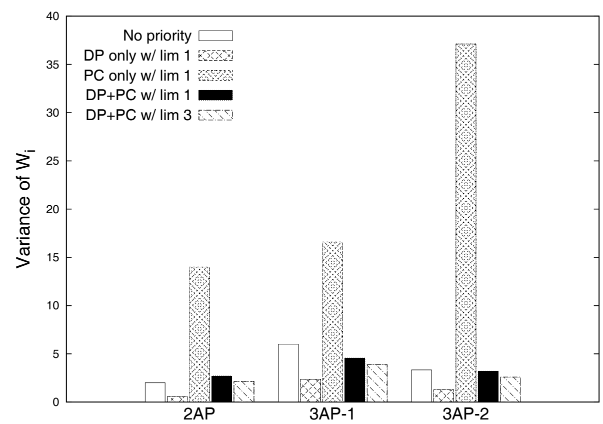

Fig. 5. The variance performances of the simple scenarios.

The variances of w_i are depicted in Fig. 5. Differently from the error performance, 'PC only w/ lim 1' and 'DP only w/ lim 1' schemes show the worst and the best variance performances, respectively. This is because the default priority and the priority compensation method only considers w_i and f_i, respectively. The variance performances of the other schemes are similar. The maximum numbers of waiting frames are 32, 10, 158, 29, and 20 in 'No priority', 'DP only w/ lim 1', 'PC only w/ lim 1', 'DP+PC w/ lim 1', and 'DP+PC w/ lim 3' schemes, respectively. They show the same tendency in the variance performance. In the simple scenarios, 'DP+PC w/ lim 1' scheme achieves 87% and 21% better performances than 'No priority' scheme in terms of error and variance, respectively.

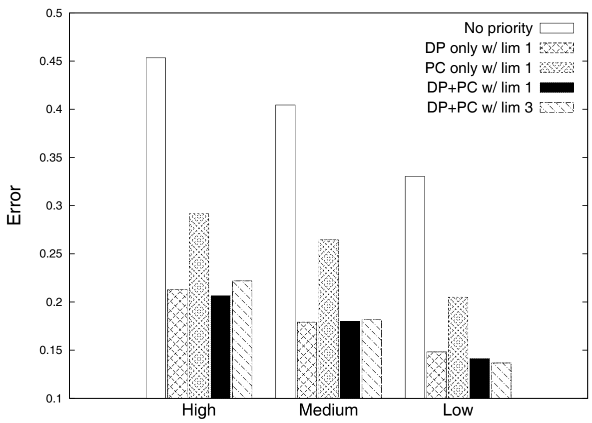

Fig. 6. The error performances of random scenarios with 50 APs.

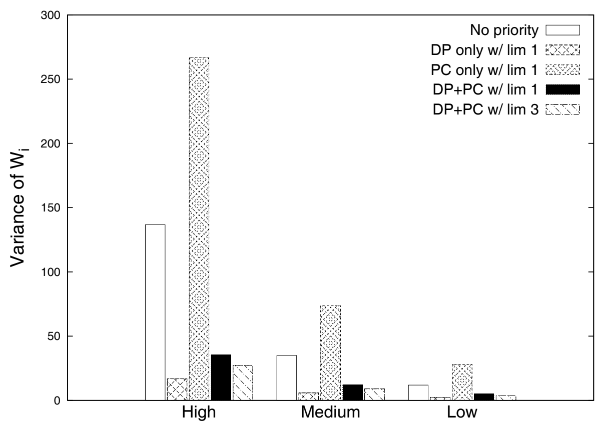

Fig. 7. The variance performances of random scenarios with 50 APs.

B. Large Scenarios

We randomly deploy 50 APs in three density scenarios: high (150m×150m), medium (200m×200m), and low (250m×250m) densities. We tested 100 random topologies for each density scenario and averaged out the results. The average numbers of neighbor APs in each density scenario are 5.14, 2.84, and 1.65, respectively. For each topology, one million frames are tested. Each AP has 1 to 4 users that are uniformly distributed and f_i is set as the number of AP i users divided by the total number of users in its contention group, i.e. $f_i = n_i / \sum_{k \in C_j} n_k$.

Fig. 6 shows the error performances of random scenarios with 50 APs. Legacy 'No priority' scheme shows the worst performance. Unlike simple scenarios, the error performance of 'PC only w/ lim 1' scheme is not good. It is because PC does not work well when an AP is connected with more than two different contention groups. However, the prioritization with DP runs well even in multiple contention group cases. In high density scenario, the performance of 'DP+PC w/ lim 1' scheme is better than that of 'DP+PC w/ lim 3' scheme. It is because the average number of neighbor APs is greater than the number of priority groups and the malfunctioning behavior of PC for a more number of priority classes. The variances of w_i are depicted in Fig. 7. It shows a similar tendency to those of simple scenarios. In random scenarios, 'DP+PC w/ lim 1' scheme achieves 56% and 66% better performances than 'No priority' scheme in terms of error and variance, respectively.

To sum up, PC shows a small error performance for the one contention group case, but it shows a weakness for a case of more than two contention groups. DP reduces the variance of the number of waiting frames, but it shows large error for the one contention group case. For a case of only two priority classes, the performance is about the same as that of four priority classes. Therefore, our proposed DP and PC prioritization scheme with priority limit of one shows good error and variance performances regardless of simple and random topology scenarios.

VI. Conclusion

Recently, contention based AP scheduling schemes have been proposed to overcome the interference problem. Since the random backoff contention method has the short-term fairness problem and it cannot differentiate priorities between APs, we proposed a prioritization scheme to solve the problems. Our proposed scheme assigns a default priority to each AP first according to the number of frames that it has been waiting for channel access. Then, we give one level higher priority to some APs through the priority compensation method. By doing so, our scheme is able to allocate a desired fraction of frames to each AP probabilistically well. Through analysis and simulation, our proposed prioritization scheme enhances the short-term fairness by 43% and gives 71% more accurate frame allocation than the legacy non-priority scheme.

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